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AEROBALLISTIC RANGE/TRACK PHOTOGRAPHIC INSTRUMENTATION DEVELOPMENT

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ARO, Inc., a Sverdrup Corporation Company

VON KÁRMÁN GAS DYNAMICS FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE 37389

April 1978

Final Report for Period July 1, 1975 - September 30, 1977

Approved for public release; distribution unlimited.

Prepared for

ARNOLD ENGINEERING DEVELOPMENT CENTER/DOTR
ARNOLD AIR FORCE STATION, TENNESSEE 37389

APPROVAL STATEMENT

This report has been reviewed and approved.

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FOR THE COMMANDER

Marion L. Laster

MARION L. LASTER
Director of Test Engineering
Deputy for Operations

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1 REPORT NUMBER AEDC-TR-77-98	2 GOVT ACCESSION NO.	3 RECIPIENT'S CATALOG NUMBER
4 TITLE (and Subtitle) AEROBALLISTIC RANGE/TRACK PHOTOGRAPHIC INSTRUMENTATION DEVELOPMENT		5 TYPE OF REPORT & PERIOD COVERED Final Report-July 1, 1975 September 30, 1977
		6 PERFORMING ORG REPORT NUMBER
7 AUTHOR(s) Paul H. Dugger, ARO, Inc.		8 CONTRACT OR GRANT NUMBER(s)
9 PERFORMING ORGANIZATION NAME AND ADDRESS Arnold Engineering Development Center/DOT Air Force Systems Command Arnold Air Force Station, Tennessee 37389		10 PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Element 65807F
11 CONTROLLING OFFICE NAME AND ADDRESS Arnold Engineering Development Center/DOS Arnold Air Force Station, Tennessee 37389		12 REPORT DATE April 1978
		13. NUMBER OF PAGES 32
14 MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15 SECURITY CLASS. (of this report) UNCLASSIFIED
		15a DECLASSIFICATION DOWNGRADING SCHEDULE N/A

16 DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17 DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18 SUPPLEMENTARY NOTES

Available in DDC

19 KEY WORDS (Continue on reverse side if necessary and identify by block number)

1 optical equipment
laser
photography
temperature measurement
2. photography
aeroballistics
ranges (facilities)
instrumentation systems

20 ABSTRACT (Continue on reverse side if necessary and identify by block number)

Development of photopyrometry systems employing state-of-the-art image intensifier devices has extended the lower limit for model surface temperature measurements in the AEDC Hyperballistic Range (G), for either free-flight or track-guided mode of operation, from 1,900 K to 1,250 K. Photographic resolvabilities (object plane) for free-flight and track versions of these photopyrometers are 300 μm (at best) and 150 μm, respectively.

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20. ABSTRACT (Continued)

Track-compatible laser photography systems have been developed that provide object-plane resolvability of 25 μm as compared to 200-μm resolvability for similar systems used in free-flight work. Stereo photography systems and an ultra-high-speed (10^7 frames per second) sequential laser photography system have been developed and applied in Track K.

AFSC
Arnold AFS Tenn

PREFACE

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65807F. The results were obtained by ARO, Inc., AEDC Division (a Sverdrup Corporation Company), operating contractor for the AEDC, AFSC, Arnold Air Force Station, Tennessee. The research was done under ARO Projects No. V32S-10A, V32I-A6A, and V34S-64A, and the manuscript was submitted for publication on September 30, 1977.

The author acknowledges the contributions of Messrs. C. P. Enis, who was instrumental in the development of photographic pyrometer systems and J. W. Hill, who was instrumental in the development of laser photography systems; both are Instrumentation Engineers of the AEDC von Kármán Gas Dynamics Facility (VKF). The author also wishes to thank Mr. R. E. Hendrix, Supervisor of the Range Instrumentation Section, VKF, for his helpful guidance and suggestions throughout the program and for his critical review of the manuscript.

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1.0 INTRODUCTION

In order to ensure against obsolescence of the aeroballistic ranges of the Arnold Engineering Development Center (AEDC) von Kármán Gas Dynamics Facility (VKF) as practical ground test facilities, it is essential to develop and expand instrumentation system capabilities to meet the imposed data acquisition requirements as areas or methods of testing change or become more sophisticated. Experimental research programs for this express purpose have been in effect for the past several years. The results from some of these past projects are presented in Refs. 1 and 2. The purpose of this report is to describe photographic instrumentation systems developed and evaluated under some of the most recent research projects.

A new type of aeroballistic range test technique, one employing a set of tracks (rails) to guide the test model along a known flight path, was recently implemented in both the 100-ft Hyperballistic Range (K) and the 1,000-ft Hyperballistic Range (G) of the VKF (Refs. 3 and 4).* Much of the work described herein was concerned with development of photographic instrumentation systems for these new facilities. In some cases, basic photographic instrumentation techniques developed for and used in the free-flight aeroballistic ranges were modified and adapted to the geometries and conditions of the new track facilities. In other cases, the fact that test models are confined to a known flight path by the track allowed applications of photographic techniques that would not have been practical in the free-flight ranges; field-of-view and depth-of-field requirements dictated by flight-path dispersion would have been prohibitive.

2.0 TRACK LASER PHOTOGRAPHY SYSTEMS

Laser photographic techniques have been routinely employed in the VKF aeroballistic ranges for obtaining high-resolution, stop-motion photographs of test models in free flight (Refs. 1 and 5 through 13). Basically, these photographic techniques utilize a pulsed ruby laser as a "flash attachment" for an open-shutter, still camera. The duration of the laser pulse (20 nsec) defines an exposure time sufficiently short to provide unblurred photographs of models in hypervelocity flight; the high power of the laser (100 MW) provides adequate energy for exposure of the film during the short exposure time; and

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*These are the formal names of the VKF aeroballistic ranges. Henceforth in this report, Range K and Track K are the names used for the 100-ft Hyperballistic Range (K) when operated in the free-flight and track-guided modes of operation, respectively. Range G and Track G are names similarly associated with the 1,000-ft Hyperballistic Range (G).

the monochromaticity of the laser allows rejection of extraneous light by selective filtering at the camera.

New laser photographic systems, employing the basic technique outlined above, were designed, developed, and put to use in the track facilities (Ref. 3). Large viewfields and depths of field are not required as they are in the free-flight aeroballistic range case.* As a consequence, it was possible to design track-compatible, single-camera systems having higher magnification, hence better photographic resolution than range systems.

The schematic of a typical laser photographic system for Track G or Track K is shown in Fig. 1. This optical arrangement provides a combination of front and back lighting through appropriate slots in the track tube. This arrangement produces a magnification of approximately 0.7, and peak photographic resolvability** of such a system has been shown to be approximately 25 μm. This compares with a peak resolvability of 200 μm with the aeroballistic range systems.

Laser photographs of test models in flight in Track K are shown in Figs. 2 and 3. Figure 2 depicts the aftermath of test model encounter with a small dust bead, and Fig. 3 depicts the imminent encounter between an erosion test model and a stream of free-falling water droplets. Visualization of the bow shock wave is provided in Fig. 3 by a striped background feature; this feature is discussed in Ref. 12. Laser photography has been used extensively in Track K to study test models in flight in clear air and in erosive environments.

In the Track G facility, seven laser photography systems are spaced along the instrumented length of the track. Laser photographs of models in flight in Track G are shown in Figs. 4, 5, and 6. Figure 4 is a photograph of a nosetip transition model, and Fig. 5 is a photograph of a transpiration-cooled nosetip (TCNT) model. Figure 6 shows the entire sequence of photographs obtained from the seven laser photography systems during the flight of an erosion test model in Track G. The effects of model encounters with erosive fields (occurring between photographic stations) are vividly illustrated by these high-resolution photographs. Such sequences of photographs have proved to be invaluable to investigators studying erosion and ablation phenomena.

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*Photographic stations near the downrange end of Range G require a staggered focus arrangement of as many as twenty-four lenses (six cameras with four lenses per camera) to accommodate flight-path dispersions. Such systems are discussed in Refs. 1, 11, and 13.

**Definition: Object-plane resolvability - Two points on an object, separated by this distance, can be resolved unambiguously in the image. This is strictly a characteristic of the optical system used and does not include motion-blur effects that result from imaging moving objects.

3.0 PHOTOGRAPHIC PYROMETRY SYSTEMS

A photographic pyrometry technique has been successfully employed for a number of years in Range G of the VKF for obtaining measurements of the surface temperatures of test models in free flight (Refs. 1, 2, 5 through 8, 14, and 15). The technique involves basically the following sequence: (1) a high-speed, image-intensifier camera system is used to obtain a stop-motion, self-luminosity photograph of the test model in flight. (2) Calibration data from a carbon-arc reference source or other blackbody source are recorded on identical film and are processed simultaneously with the model photograph. (3) Densities on the film image are measured and converted to temperatures using the calibration data.

The primary component in the photopyrometry technique outlined above is the image-intensifier device, and the overall sensitivity of the photopyrometer to temperature is determined primarily by the spectral response and gain of the image intensifier. The capability for detection of longer wavelength incandenscent radiation and/or greater intensification (higher gain) allows measurements of lower temperatures.

The initial aeroballistic range photopyrometry systems (Refs. 1, 5 through 7, 14, and 15) were developed (circa 1970) for use during ablation and erosion testing wherein surface temperatures of interest generally fell within the 3,000- to 4,000-K range. The lower temperature measurement limit for these systems, which employed then state-of-the-art, proximity-focused (diode type) image intensifiers with S-11 spectral response (0.35 to 0.65 μm) and with relay lenses for transferring the intensified image to the recording film, was on the order of 2,800 K. Other types of aeroballistic range testing, e.g., nosetip transition and transpiration-cooled nosetips, required measurements of surface temperatures at levels below the 2,800-K limit of the initial systems. It thus became a continuing goal of instrumentation research efforts to extend the lower measurement limits for Range G photopyrometers. Progress of any significance toward this goal was contingent on advances in the state-of-the-art of image intensifiers. Fortunately, over the ensuing years, manufacturers have developed several significantly advanced types of image tubes. Commercial availability of these advanced devices was followed in a stepwise manner by developments of improved photopyrometers (lower temperature measurements limits) for Range G. Table 1 chronologically summarizes the state-of-the-art intensifier advances and the corresponding extensions of the lower temperature measurement capability that have resulted.

All photopyrometers presently in use employ image intensifiers of either the 1975 (Gen. I) or 1976 (Gen. II) vintage. These advanced photopyrometers were applied initially for measurements during free-flight tests in Range G. The photopyrometer configuration was basically the same as that given in Refs. 1, 2, 5 through 8, 14, and 15; only the

image-intensifier component was different. Figure 7 is an isothermal contour map resulting from use of one of the Gen. II pyrometers during a Range G test of a transpiration-cooled nosetip model. (The nosetip portion of this TCNT model was very similar to the nosetip of the track version shown in Fig. 5.) Obviously, none of these important data could have been acquired using pre-1976 photopyrometers (Table 1).

Recently, photopyrometers were adapted for use in the Track G facility. A Track G system is shown schematically in Fig. 8. The image-intensifier camera is located inside the range tank, much closer to the model than was the case with Range G (free-flight) systems wherein large viewfields were necessary to accommodate flight-path dispersions. This ability to move closer to the model results in better photographic resolution and allows use of smaller diameter intensifier tubes. Overall magnification with the arrangement of Fig. 8 is 0.3, and object-plane resolvability is approximately 150 μm. Corresponding values for Range G systems were 0.15 and 300 μm for uprange systems and 0.08 and 600 μm for downrange systems.

As shown in Fig. 8, a front-surface mirror placed inside the track tube affords a viewing angle of 5 deg from head-on. This viewing angle, desirable for near-normal viewing of the stagnation point regions of test models, tends to minimize motion blur. For example, an exposure time of 100 nsec will result in a motion blur of only 40 μm for a model velocity of 5,000 m/sec.

Track G photopyrometer systems were mechanically designed so that the image-intensifier cameras can be removed conveniently and transported to the laboratory for calibration. Graphite-arc lamps and other lower temperature blackbody sources are maintained as temperature standards in the laboratory.

To ensure that photopyrometry systems detect only incandescent radiation from the model surface and thus provide accurate measurements of model surface temperature, it is necessary to quench, or considerably diminish, chemiluminescence and shock cap radiation. This is achieved in Track G via use of helium-filled chambers at each photopyrometry measurement station (Ref. 3). Each photograph (surface temperature measurement) is made while the model is temporarily in flight within an inert helium atmosphere. (This technique is also used in Range G.)

A self-luminosity photograph of a nosetip transition model in flight in Track G is shown in Fig. 9. (A laser photograph recorded during this same shot is shown in Fig. 4.) This photograph was recorded with a Gen. II photopyrometer operated with an exposure time of 1,000 nsec. The surface temperature information extracted from the nosetip portion of this photograph is presented in Fig. 10. The lower measurement limits of pre-1975 photopyrometers (Table 1) would have precluded acquisition of any of the temperature data of Fig. 10.

The total surface temperature measurement capability in Track G is summarized in Table 2. The photopyrometers can be operated at any five of six possible locations along the 1,000-ft test section of Track G.

4.0 STEREO LASER PHOTOGRAPHY

Early investigations (Ref. 1) into the possibility of applying high-speed stereo photography techniques in the free-flight aeroballistic range eventually led to the conclusion that this was not practical because of the requirements for quite large fields of view and depths of field to accommodate flight path dispersions. The strict flight path confinement afforded by the new track facilities relaxed these prohibitive requirements so that application of stereo photography techniques became feasible.

A stereo photography technique using laser illumination was designed for Track K as a method for obtaining in-flight crater measurements. This stereo photography technique is similar to one used at the University of Dayton Research Institute (UDRI) and reported in Ref. 16. As shown in Fig. 11, the model nose is illuminated by diffuse laser light (pulsed ruby laser), and a stereo pair of cameras (fabricated by and the property of the UDRI) views the model nose from the left and right at angles of approximately 20 deg from head-on. An example of a stereo pair of photographs of a test model in flight in Track K is shown in Fig. 12. Two discrete craters on the model nose caused by impacts with water droplets are readily discernible, as are model ejecta resulting from the impacts. These stereo photographs were recorded 625 μsec (~1.5 m) after the initial model/droplet encounters.

The pair of photographs in Fig. 12, along with a second stereo pair made of this same model after recovery, were sent to a commercial mapping concern for reconstruction and analysis. Results of this analysis are shown in Fig. 13. These are the elevation contour profiles for the two craters, for both the in-flight and static or recovered cases. Contour intervals are approximately 0.2 mm; crater diameters are on the order of 5 mm; and crater depths are on the order of 1.5 mm. Crater volumes were calculated by further analysis of these data. The calculated volume for the upper crater in the in-flight case agrees with the calculated volume for this same crater in the recovered model to within about four percent, the crater in the recovered model being larger. For the lower crater, which is seen in photographs of Fig. 11 to have been still losing material, the calculated volumes differ by about 20 percent, the value for the recovered model case again being larger.

The crater volumes calculated from stereo data (recovered model case) compare extremely well with physical volume measurements made on the recovered model. Stereo measurements agree with physical measurements to within two percent and seven percent for the upper and lower craters, respectively.

5.0 SEQUENTIAL LASER PHOTOGRAPHY SYSTEM

An innovative sequential laser photography system was designed and successfully applied in Track K for the observation of one-on-one encounters between erosive particles and the test model/bow shock. Development of such a system was made possible by the controlled trajectory feature of the track facility. As with the stereo system discussed in the preceding section, viewfield (particularly, depth of field) requirements for application in the free-flight range would have been prohibitive.

The sequential laser photography system, shown schematically in Fig. 14, consists essentially of five individual back-light laser photography systems located very close to one another. Images formed by the five individual back-light systems are separated from one another geometrically; i.e., light from one particular laser enters only one particular lens of the multilens camera. A pictorial of the arrangement of the five lasers is given in Fig. 15a and the multilens camera is pictured in Fig. 15b. Specially designed electronics allow the time between laser firings (photographic exposures) to be varied from 100 nsec to 100 μsec. At the minimum time between frames of 100 nsec, an effective framing rate of 10^7/sec is achieved.

Examples of the use of the sequential laser photography system in Track K are shown in Fig. 16. In Fig. 16a, 1-mm-diam water droplets in free fall are shown between the model and its bow shock, and then the encounter of one of the water droplets with the model surface is depicted over a period of 2 μsec, at a framing rate of 2×10^6/sec. Figure 16b shows the simultaneous encounters of two water droplets with a model surface at a framing rate of slightly less than 2×10^6/sec. Conditions on this shot were almost identical to those on the shot during which the stereo photographs of Fig. 12 were recorded. In Fig. 16c, three water droplets approximately 1 mm in diameter are pictured in free fall just outside the model bow shock, then the droplets are shown inside the bow shock, and finally the sequence is completed in the frame depicting the aftermath of impact with the model surface.

6.0 CONCLUDING REMARKS

Extension of the lower limits for model surface temperature measurements has allowed successful conduction of transpiration-cooled nosetip and nosetip transition types of testing in Range/Track G. The majority of the surface temperature information that is of primary interest during these types of tests could not have been recorded without the latest state-of-the-art photopyrometers that allow measurements as low as 1,250 K.

In applying photographic instrumentation to the free-flight aeroballistic range, one is almost always forced to trade off photographic resolution to achieve the large depths

of field and fields of view necessary to accommodate flight path dispersions. The track facilities, which provide a known, confined flight trajectory for test models, allow these trade offs to be reversed. Photopyrometry and laser photography systems developed for the track facilities have significantly better photographic resolution than do their aeroballistic range counterparts. Photographic resolvability (object-plane) for track-compatible photopyrometers is 150 μm as compared to 300 μm for the best of those used during free-flight testing; resolvability for systems used near the downrange end of the free-flight range, where very large viewfields are required, is approximately 600 μm. Track laser photography systems have resolvabilities of 25 μm as compared to 200 μm for range systems.

The confined trajectory feature of the track facilities also allowed the development of stereo photography and sequential laser photography systems. These systems, which would not have been practical for application in the free-flight range, were demonstrated to provide valuable information during erosion testing in Track K.

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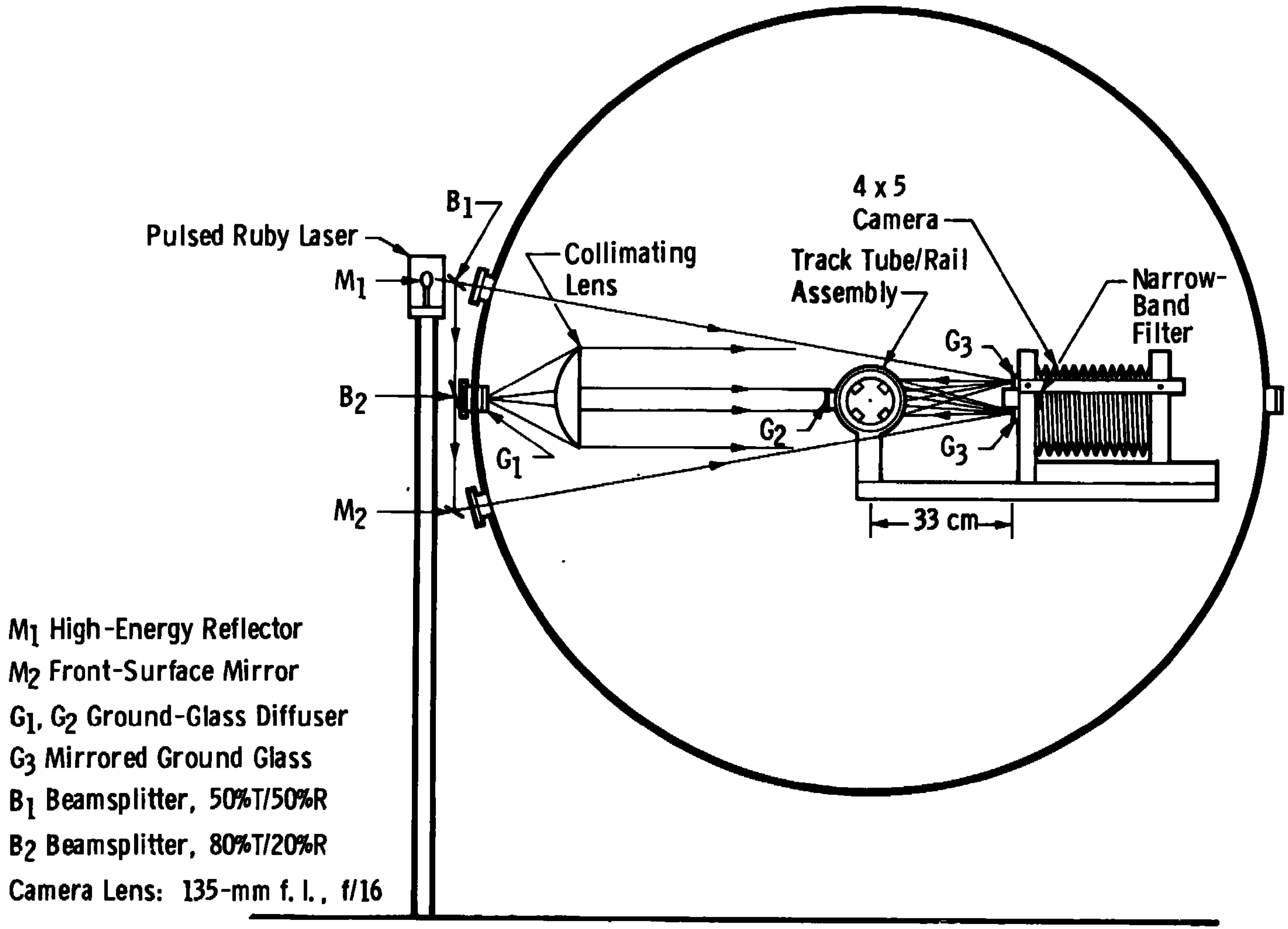


Figure 1. Track front-light/back-light laser photography system.

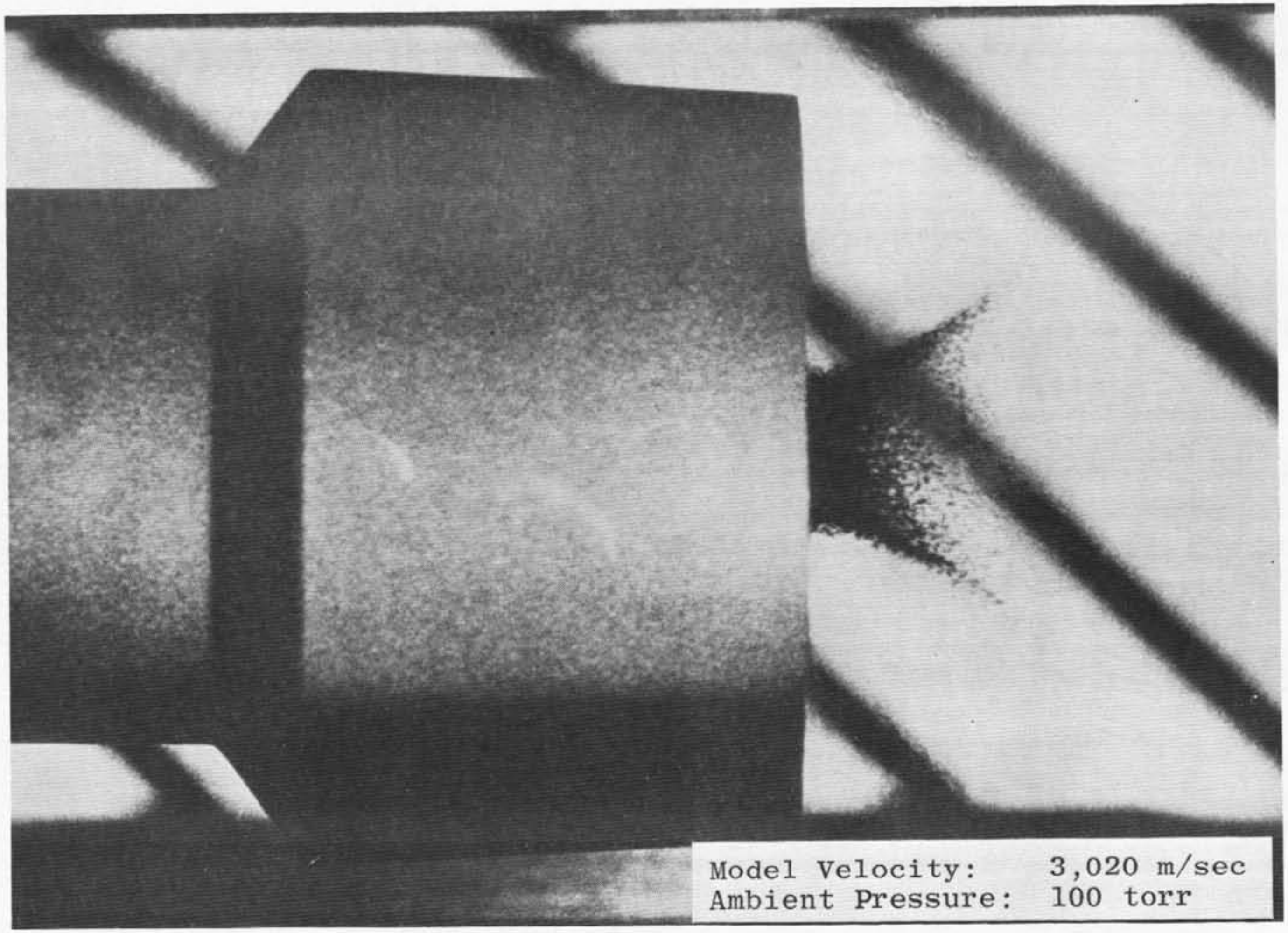


Figure 2. Laser photograph of track-guided model/dust particle encounter, Track K.

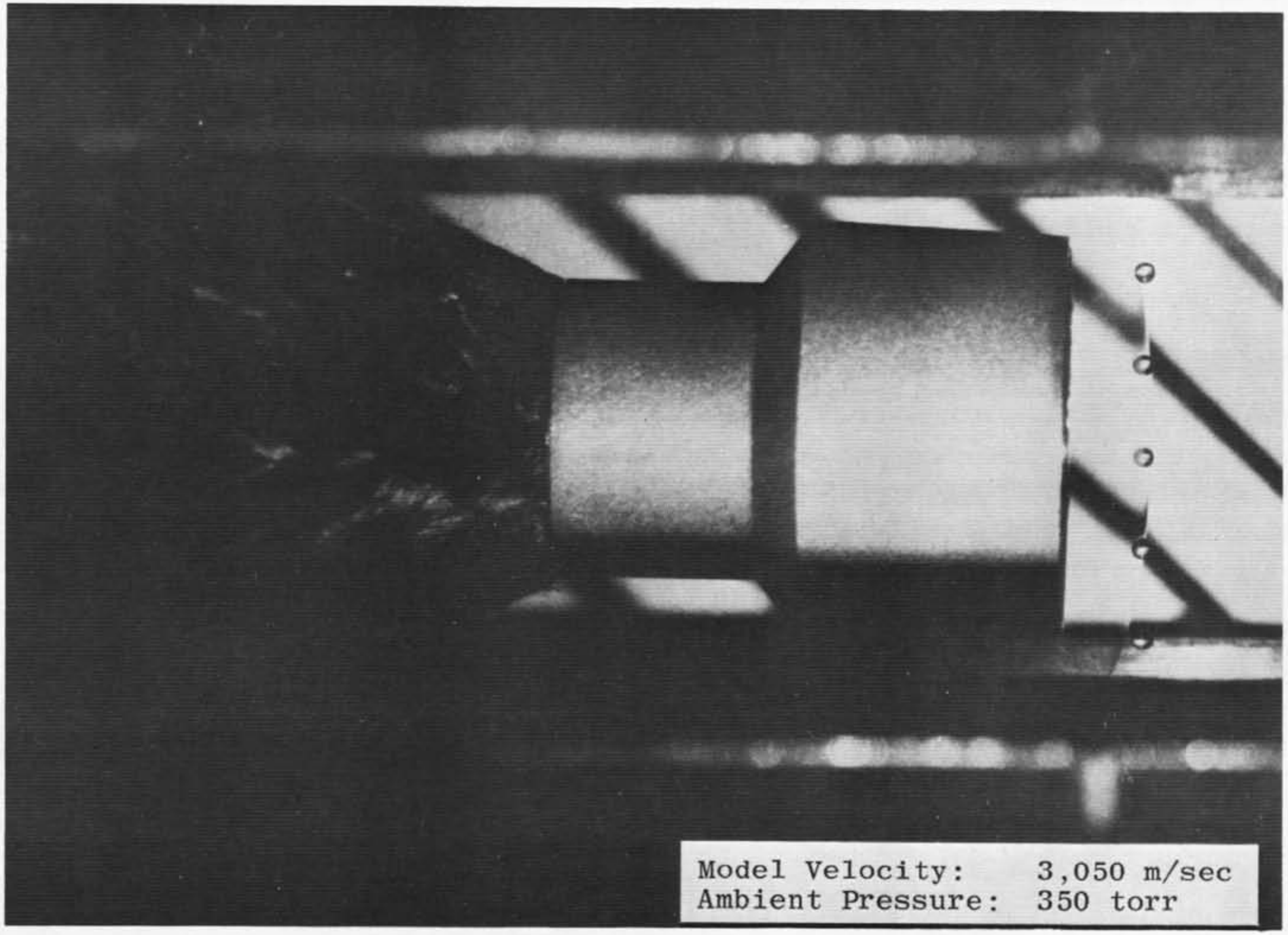


Figure 3. Laser photograph of track-guided model before impact with a stream of water droplets, Track K.

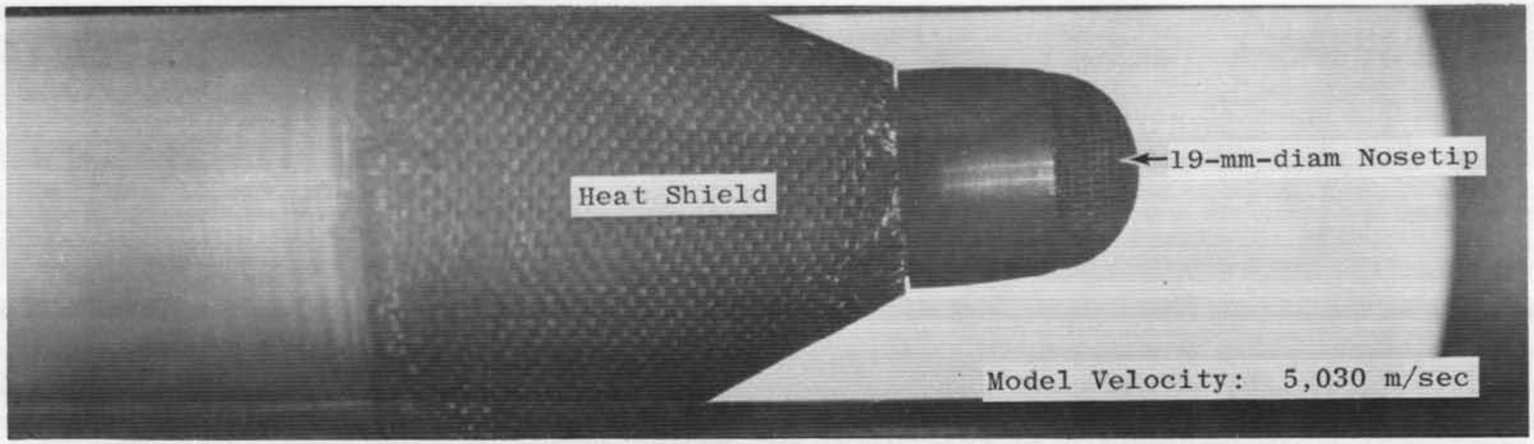


Figure 4. Laser photograph of nosetip transition model in flight in Track G.

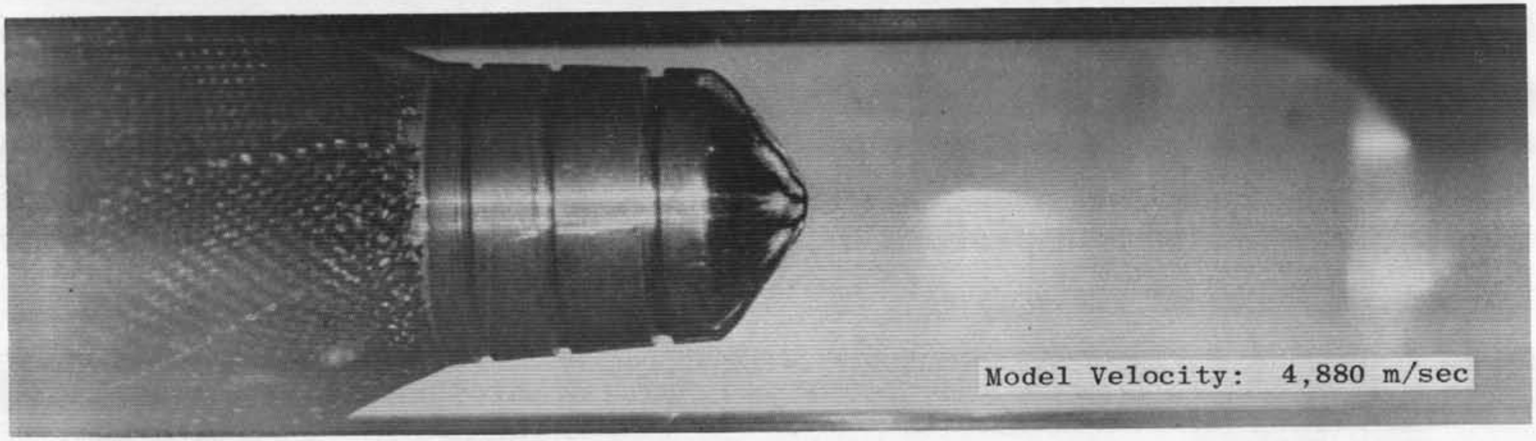
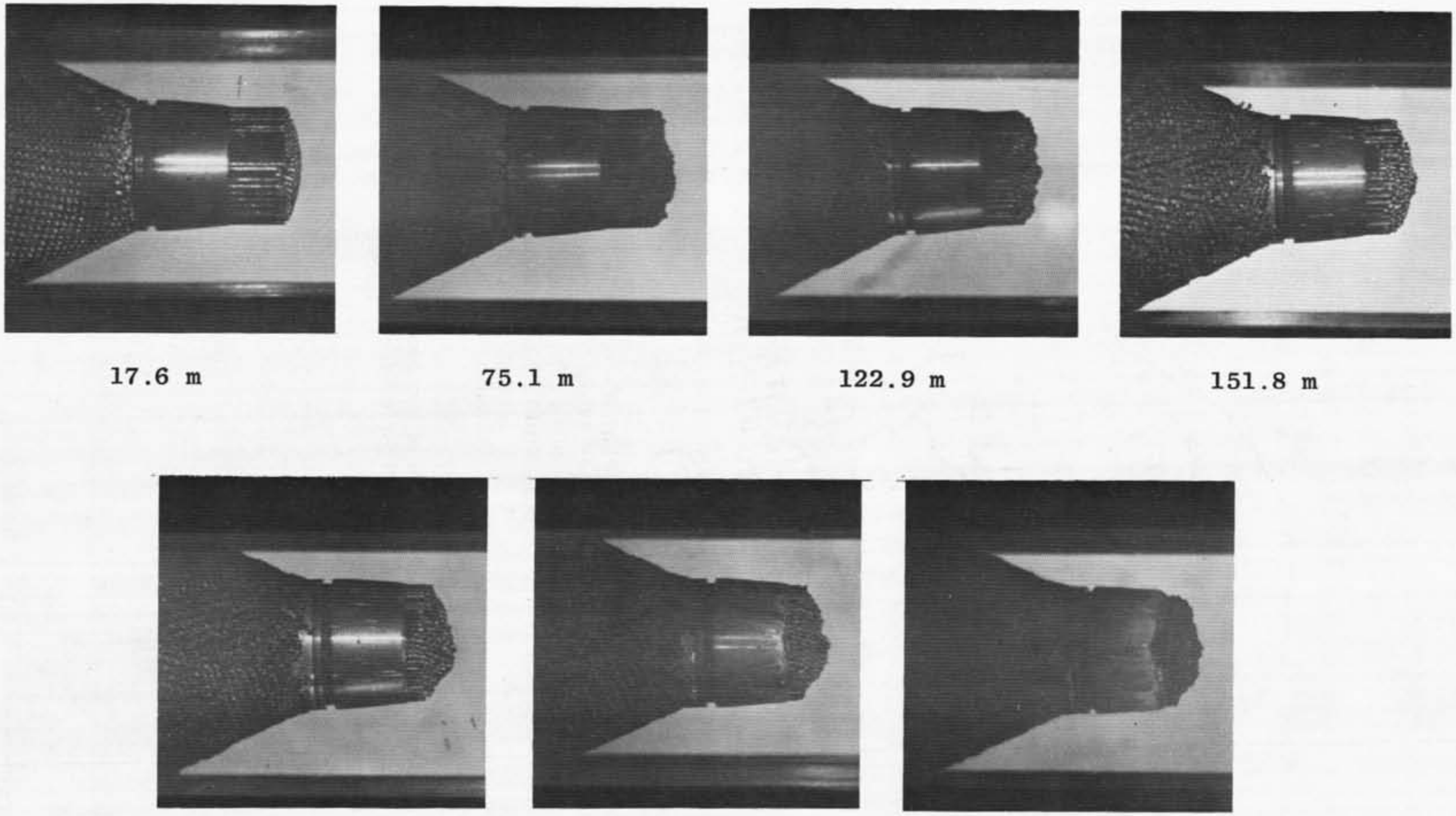


Figure 5. Laser photograph of transpiration-cooled nosetip model in flight in Track G.

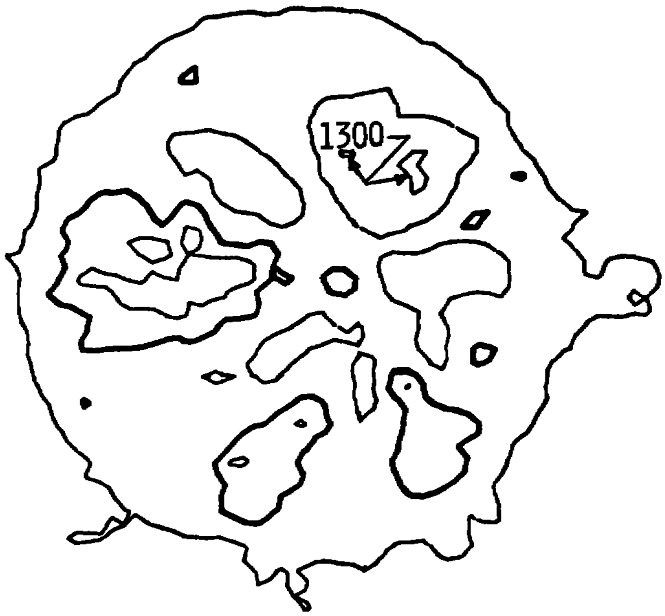


17.6 m　75.1 m　122.9 m　151.8 m

183.8 m　221.4 m　258.0 m

Note: Flight distances are referenced to range entrance.

Figure 6. Sequence of photographs from Track G front-light/back-light laser photography systems.



Legend

Heavy Contours: 1,500 K
1,300 K Contours Are Indicated
All Other Contours Are 1,400 K

Notes

1. Instrumentation System: Gen. II Photopyrometer
2. Nosetip Diameter: 25 mm
3. Model Velocity: 4,880 m/sec
4. Viewing Angle: 10 deg from Head-On

Figure 7. Isothermal contour map of transpiration-cooled nosetip model in free flight in Range G.

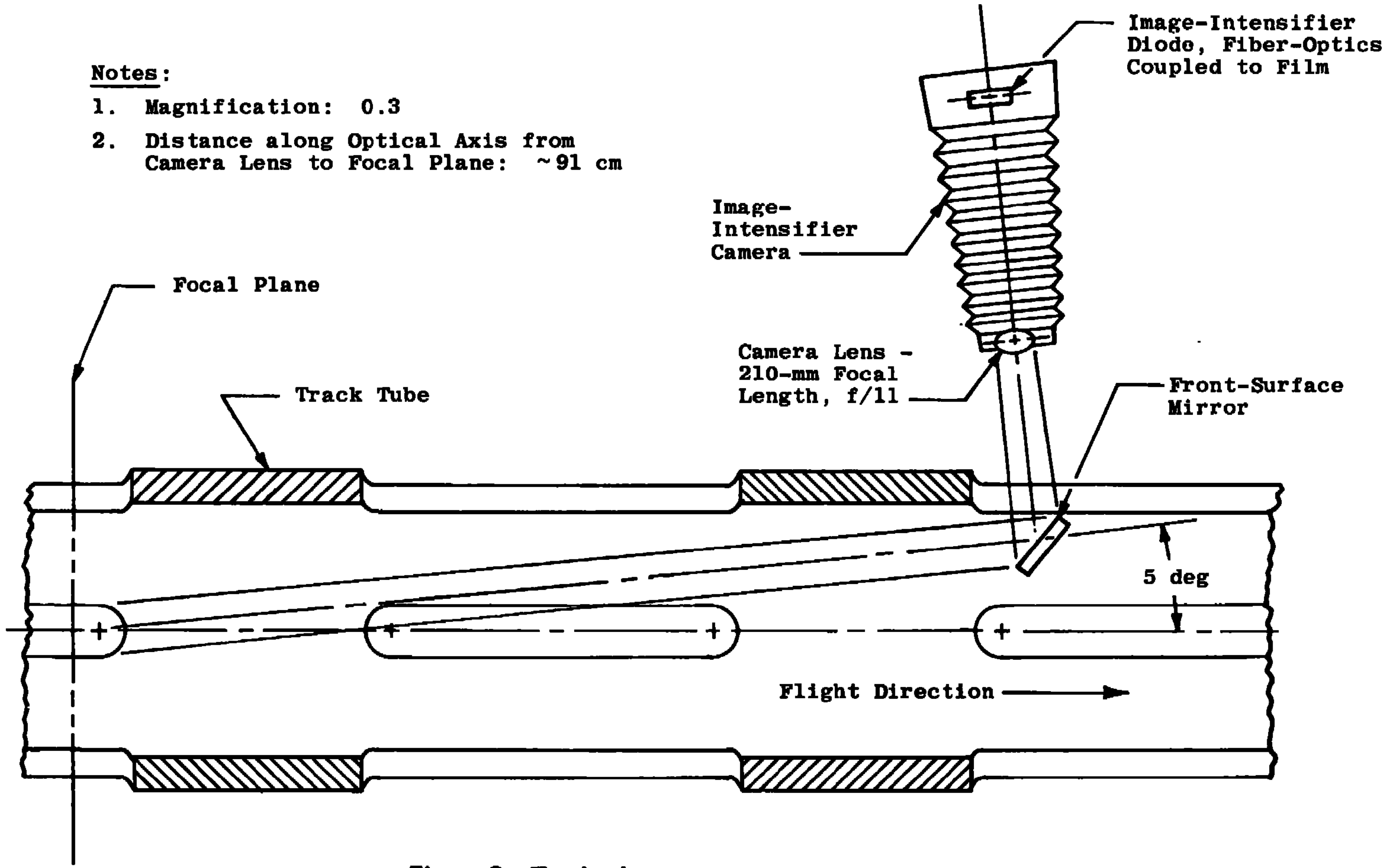


Figure 8. Track photopyrometer arrangement.

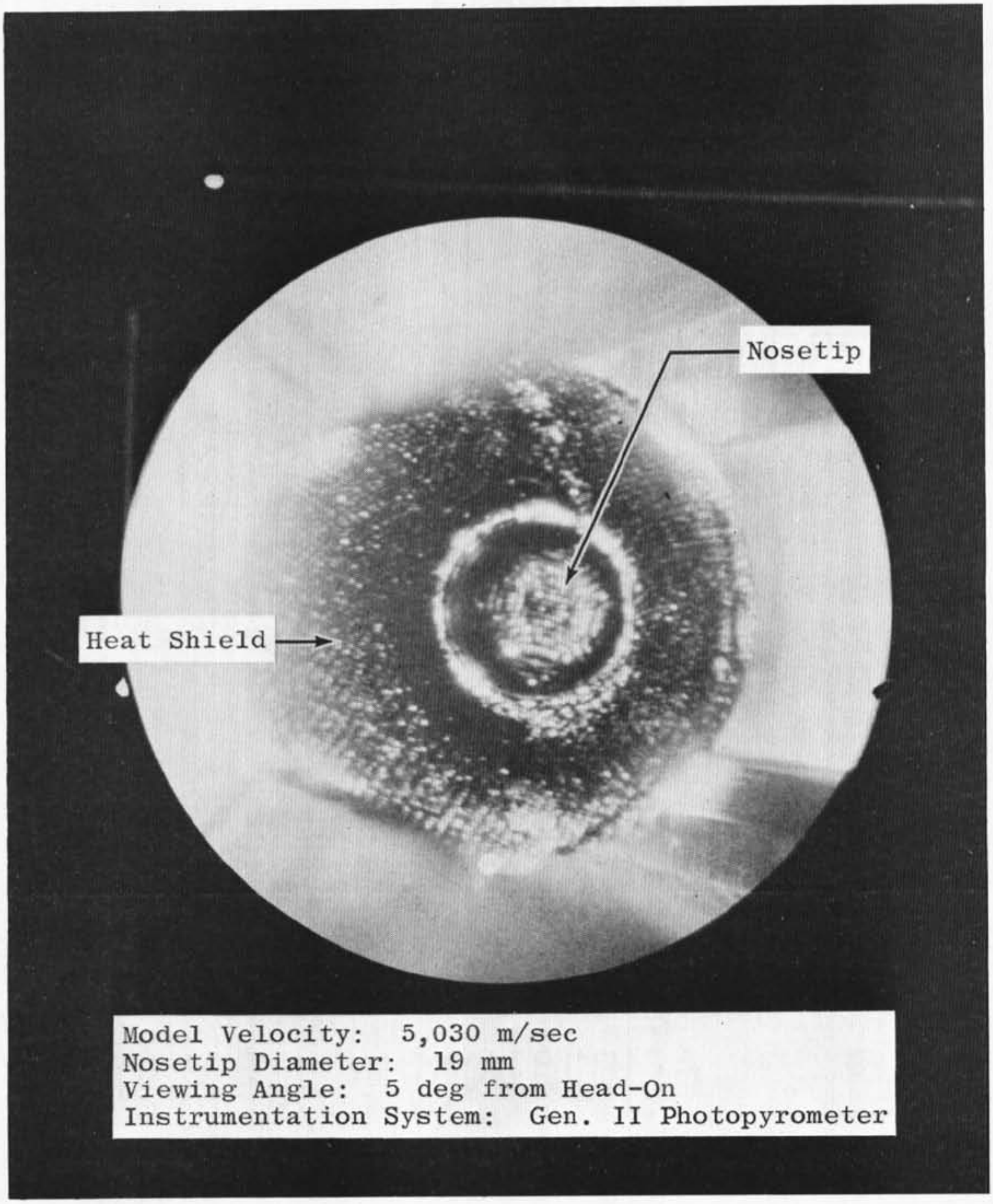
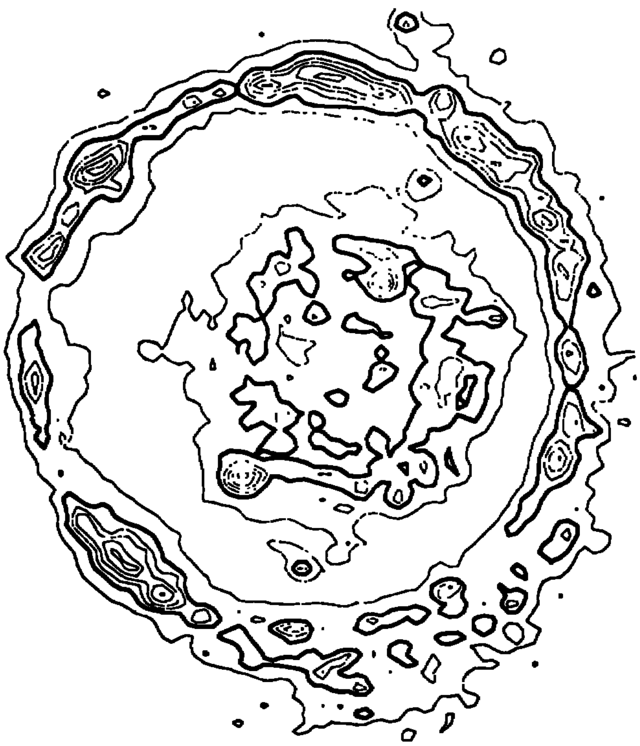


Figure 9. Self-luminosity photograph of nosetip transition model in Track G.



Legend

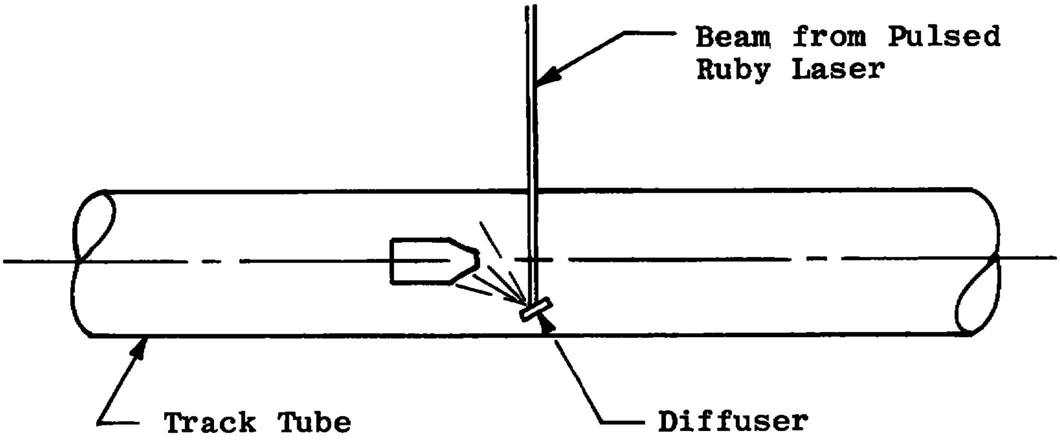
Contour Intervals: 100 K

Heaviest Lines Are 1,500-K Isotherms

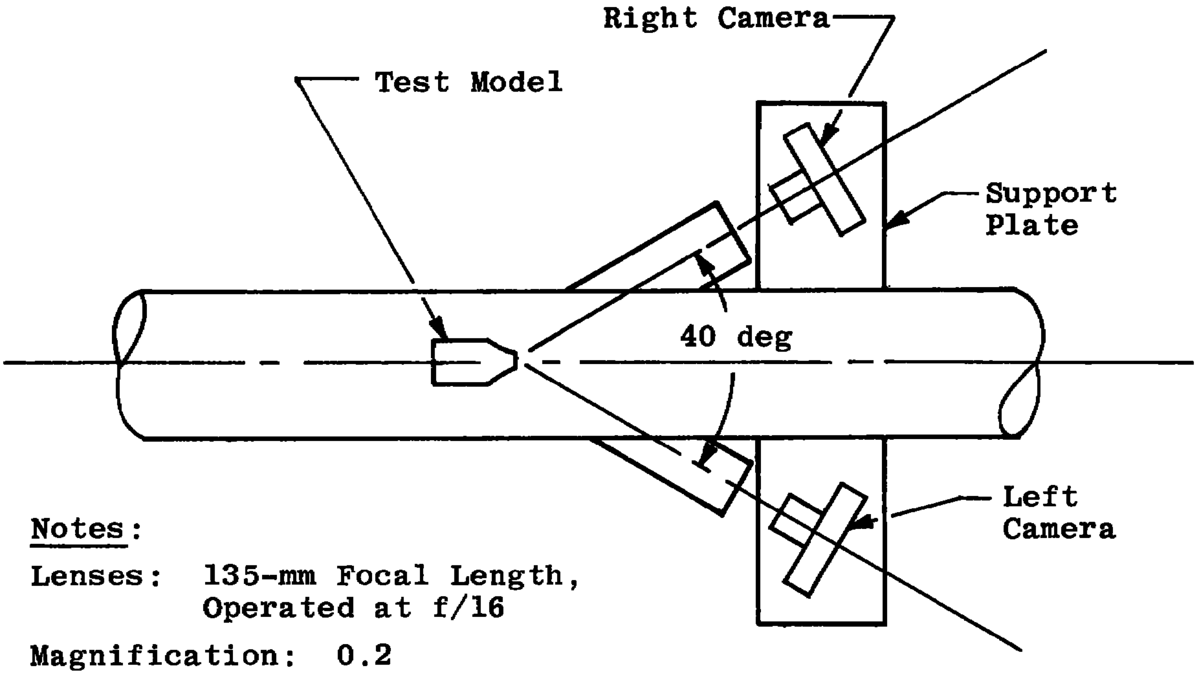
Notes

1. Instrumentation System: Gen. II Photopyrometer
2. Nosetip Diameter: 19 mm
3. Model Velocity: 5,030 m/sec
4. Viewing Angle: 5 deg from Head-On
5. Laser Photograph of Model Is Shown in Fig. 4

Figure 10. Isothermal contour map of nosetip region of nosetip transition model.

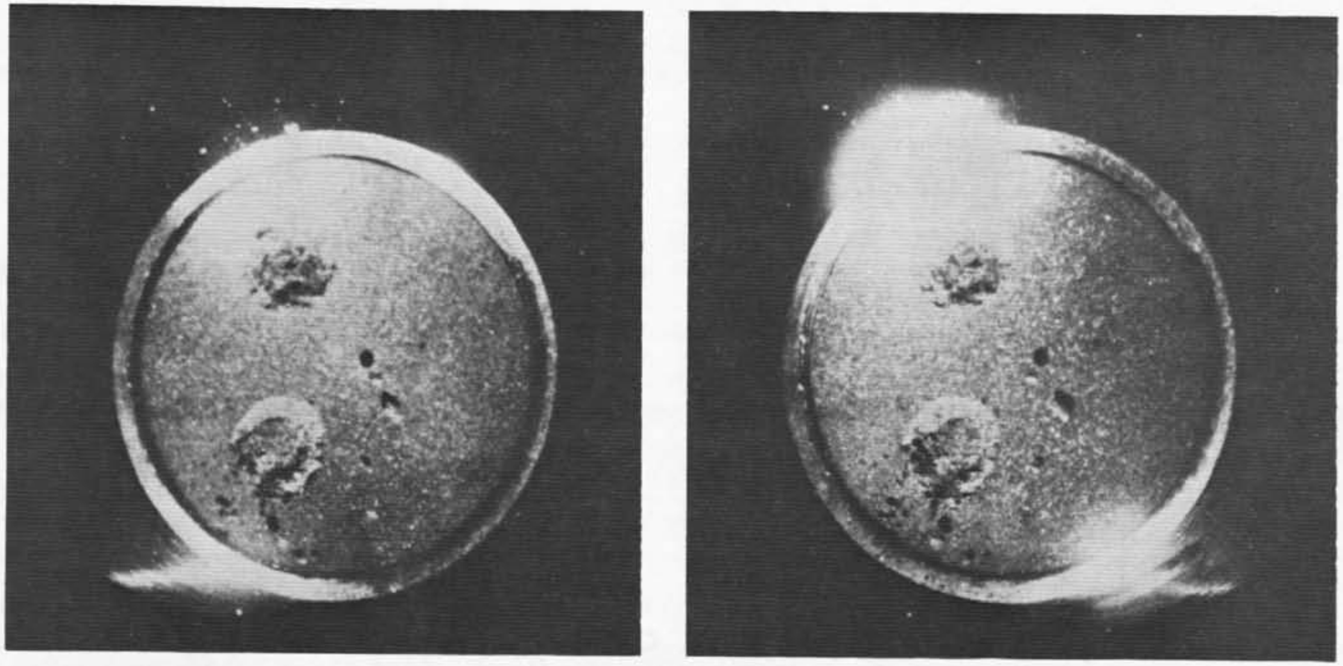


a. Illumination scheme (side view)



b. Stereo camera arrangement (top view)

Figure 11. Track stereo laser photography system.



Model Velocity: 2,440 m/sec
Total Angle between Cameras: 40 deg

Figure 12. Stereo photographs of laser-illuminated track K model.

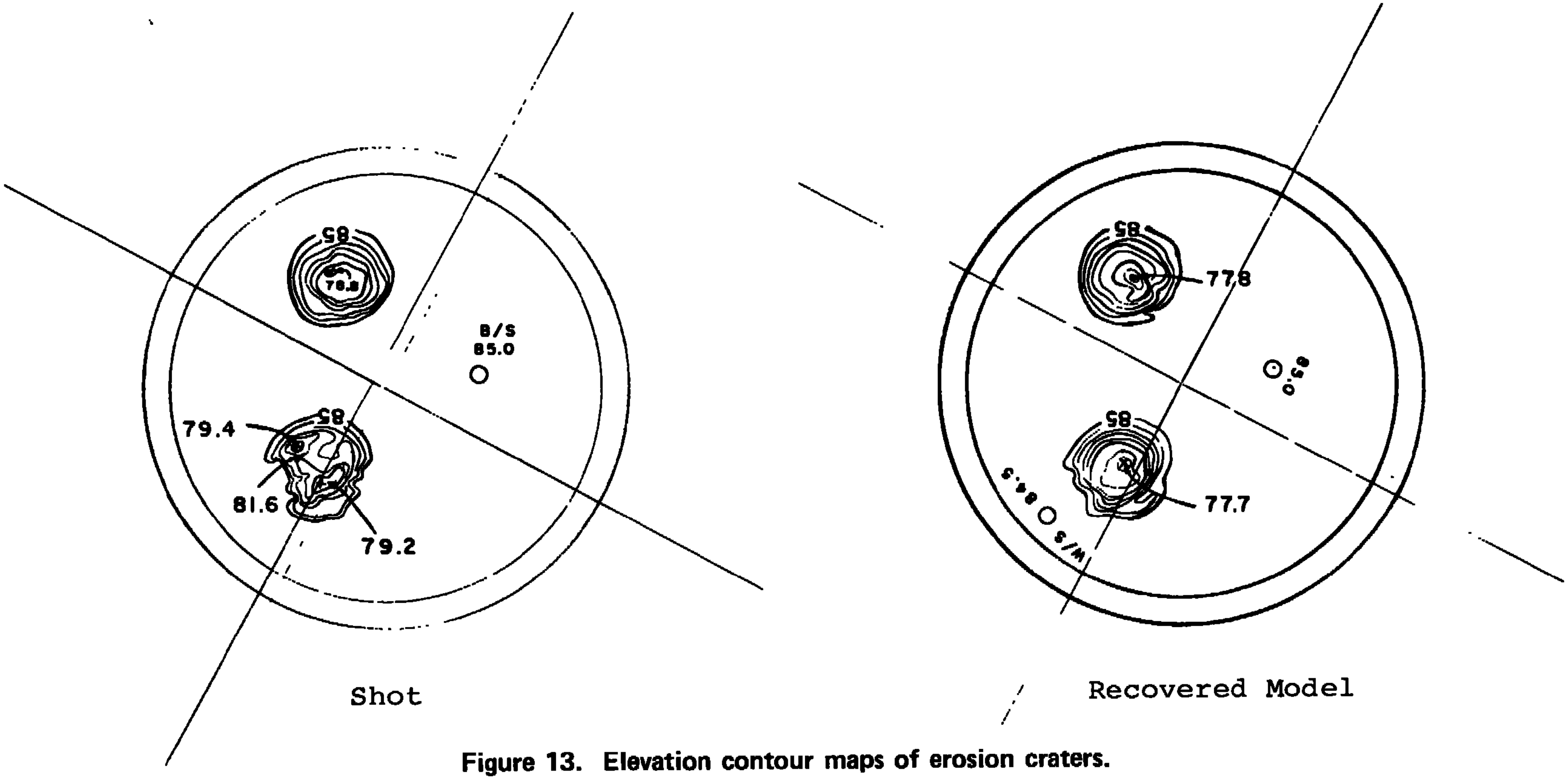


Figure 13. Elevation contour maps of erosion craters.

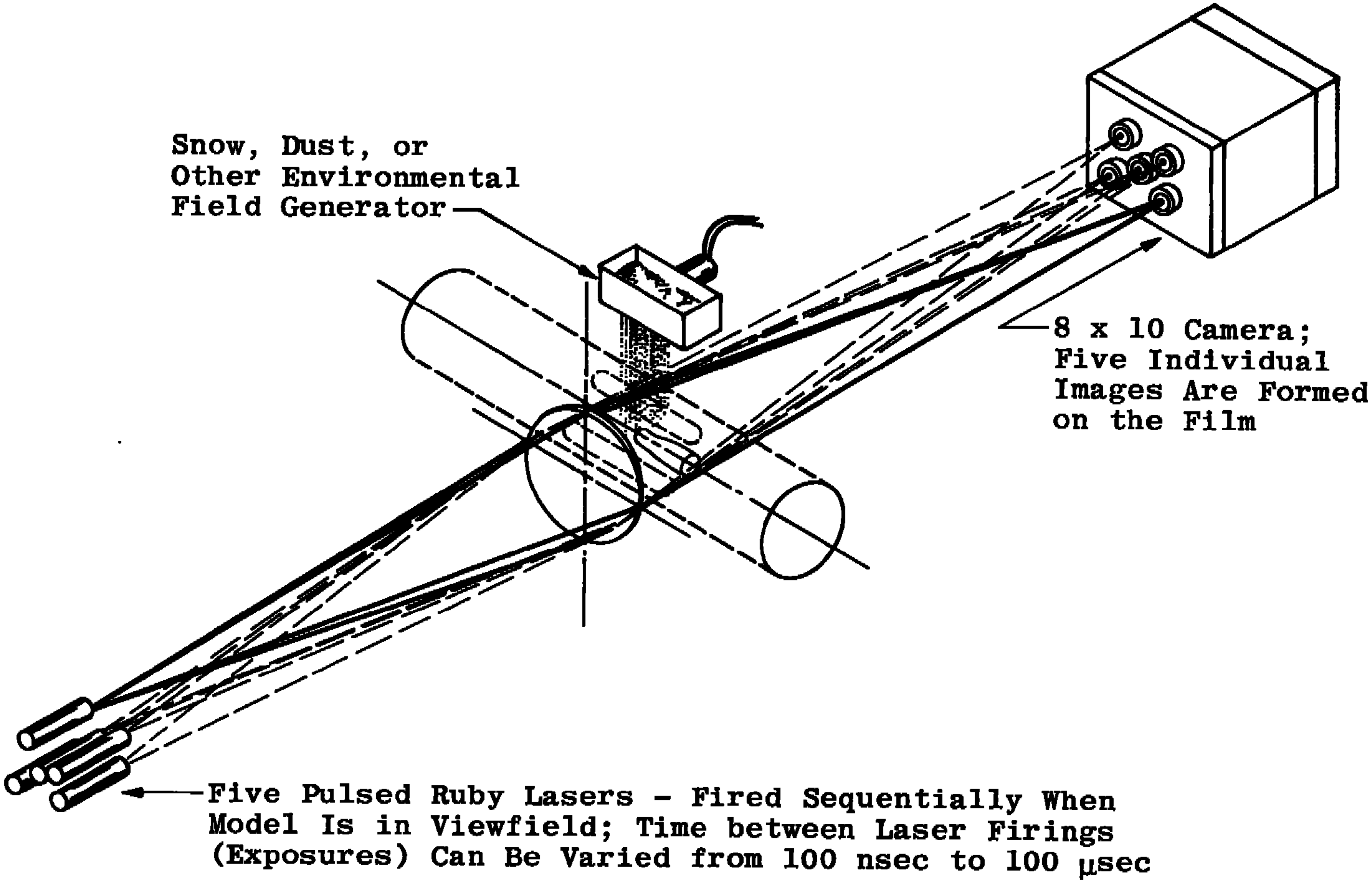
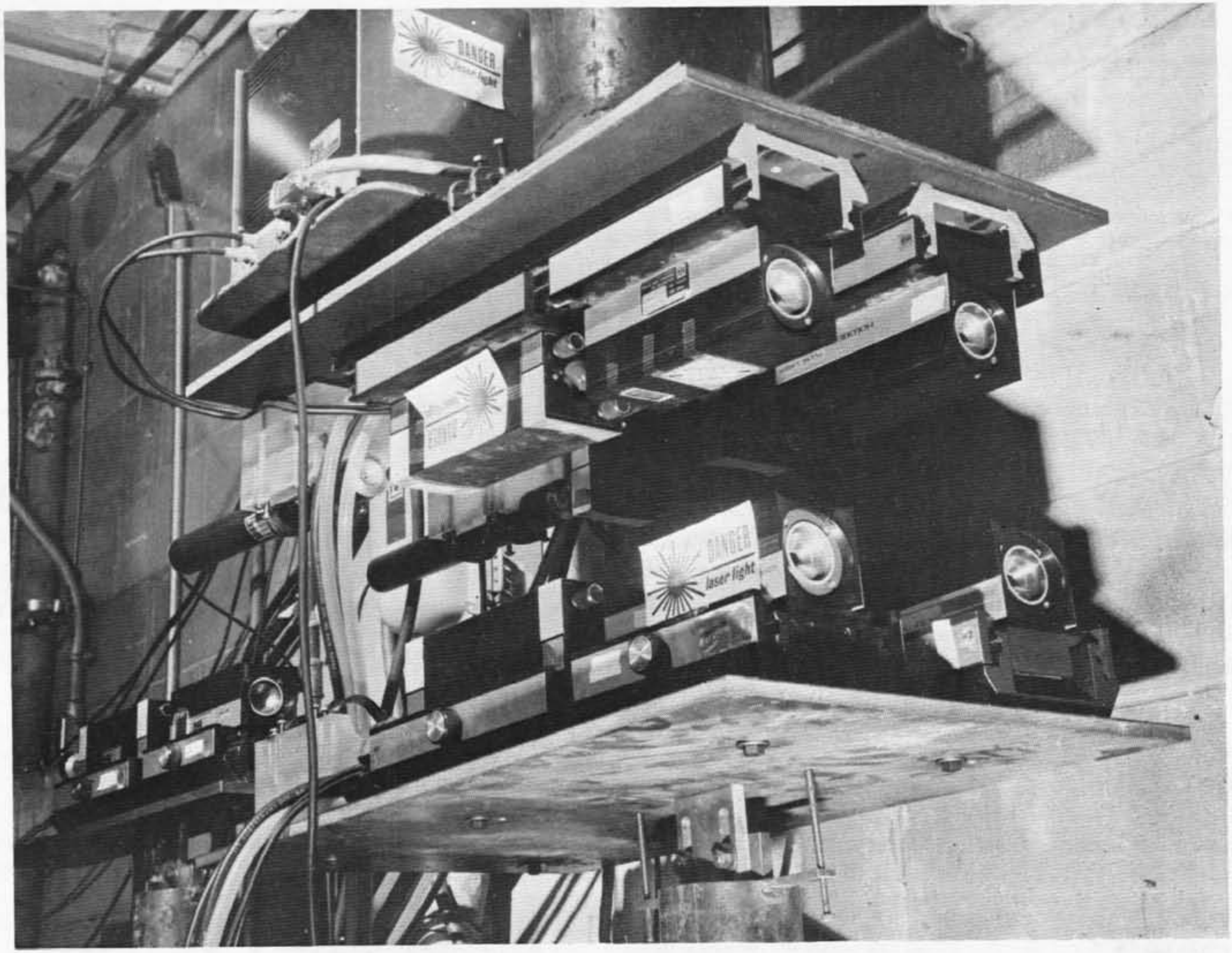
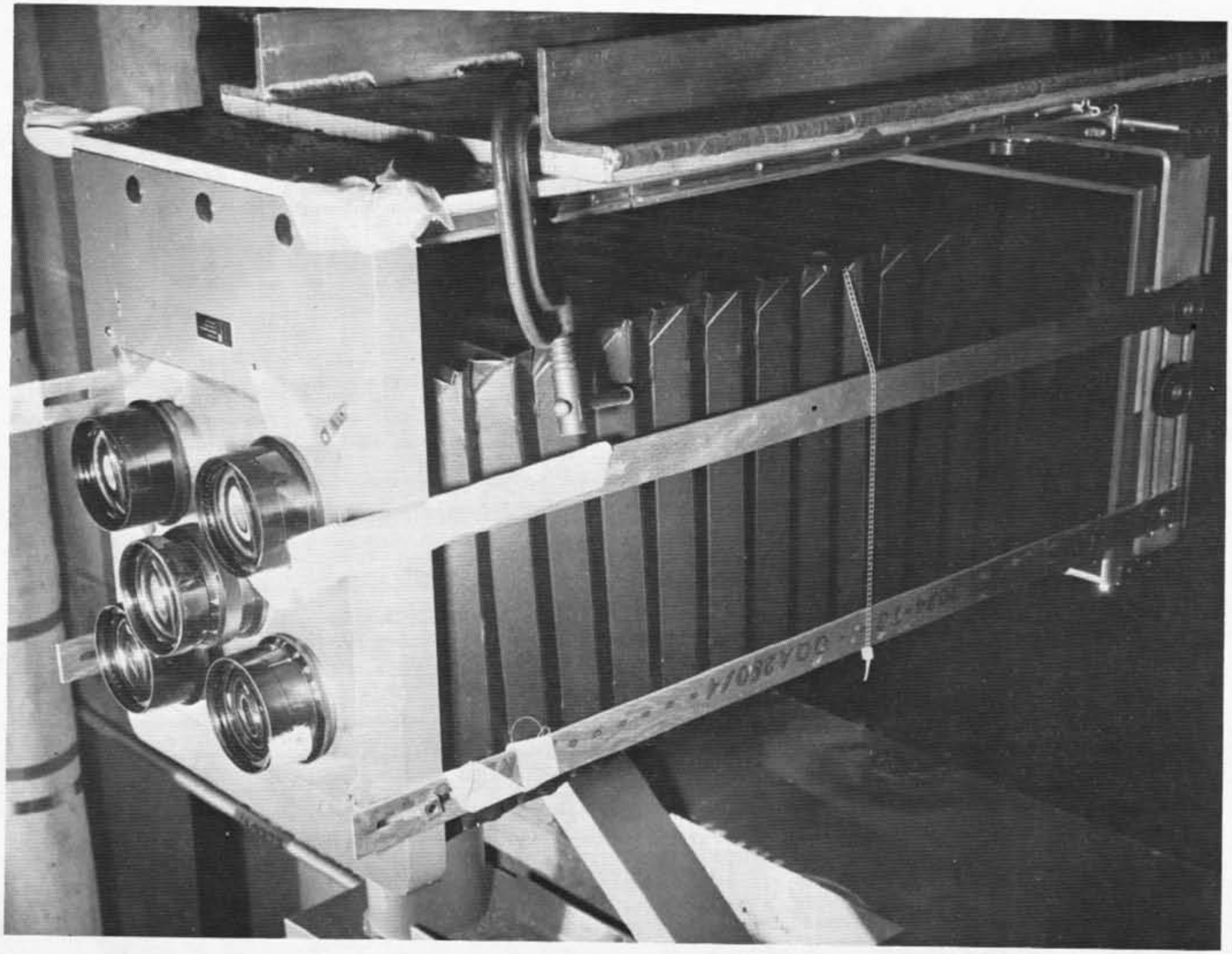


Figure 14. Sequential laser photography system.

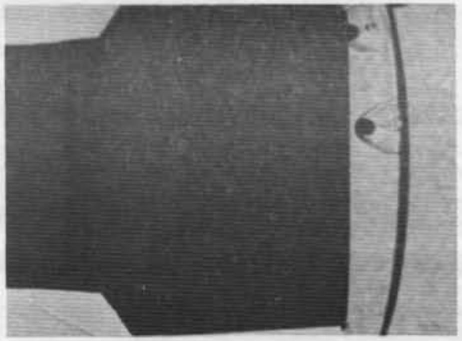


a. Five laser systems

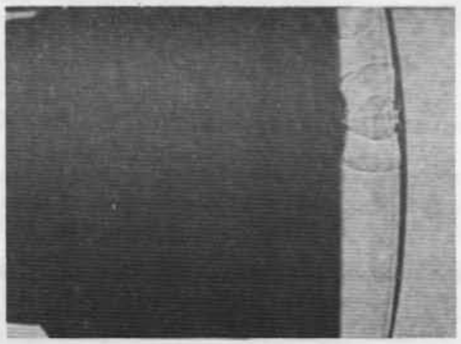
Figure 15. Components of sequential photography system.



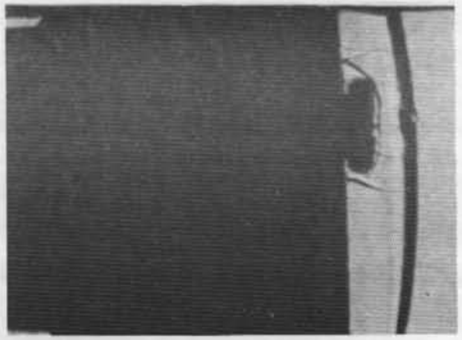
b. Multilens camera
Figure 15. Concluded.



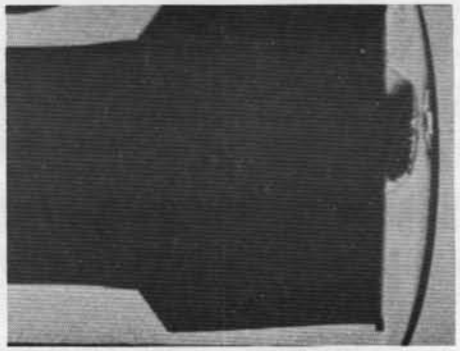
t = 0



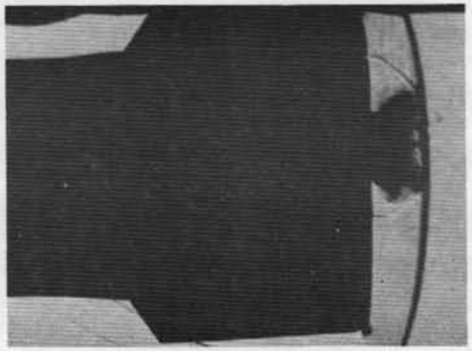
t = 0.5 μsec



t = 1.0 μsec



t = 1.5 μsec

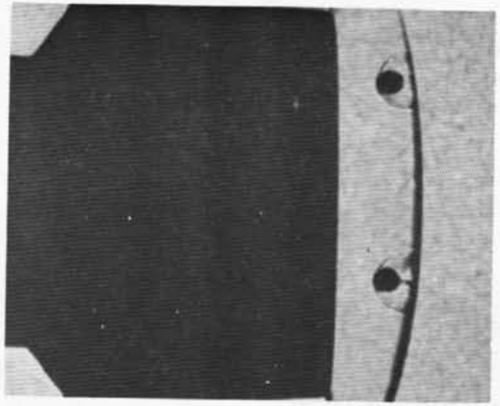


t = 2.0 μsec

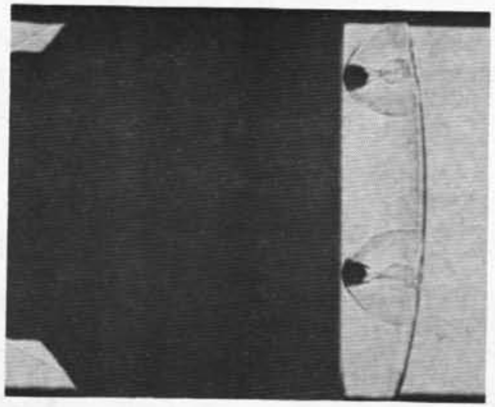
Model Velocity: 3,660 m/sec
Range Pressure: 350 torr
1-mm-diam Water Droplets

a. One impact

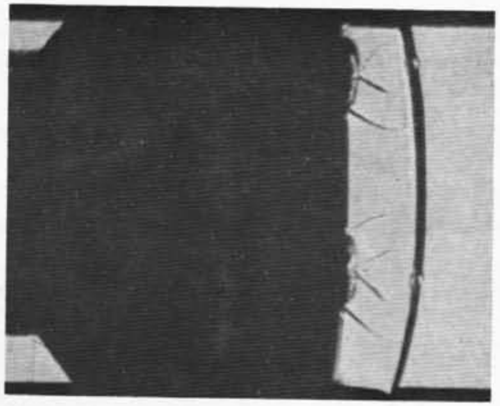
Figure 16. Sequential laser photographs depicting model and bow shock interaction with water droplets in Track K.



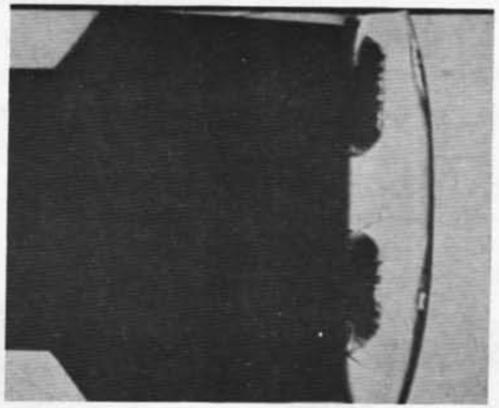
t = 0



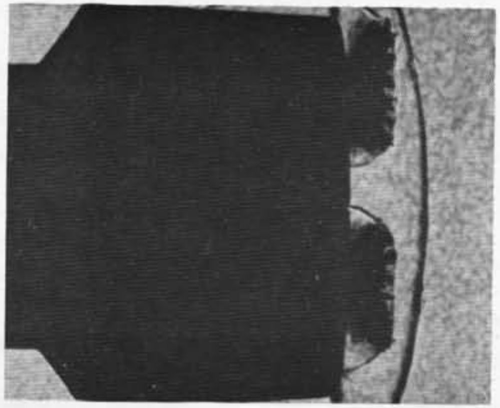
t = 0.6 μsec



t = 1.2 μsec



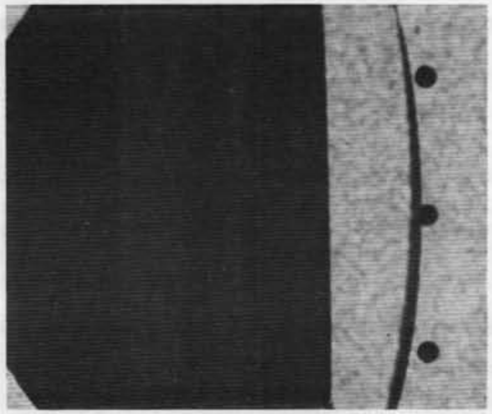
t = 1.8 μsec



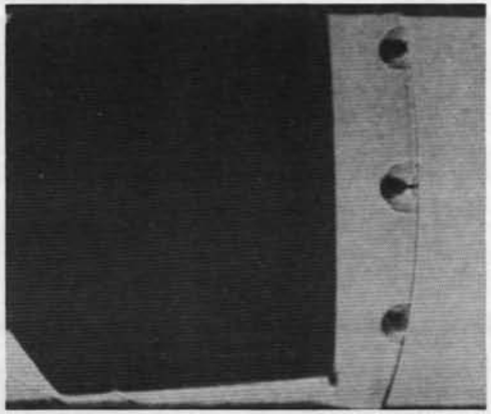
t = 2.4 μsec

Model Velocity: 2,460 m/sec
Range Pressure: 354 torr
1.2-mm-diam Water Droplets

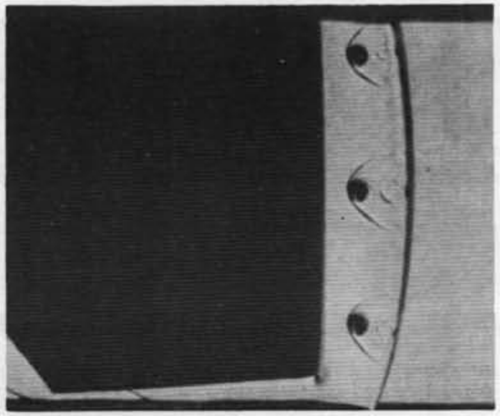
b. Two impacts
Figure 16. Continued.



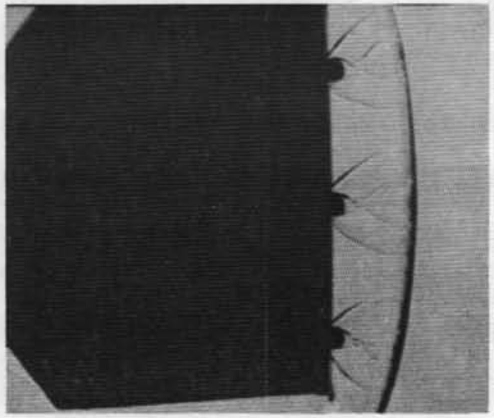
t = 0



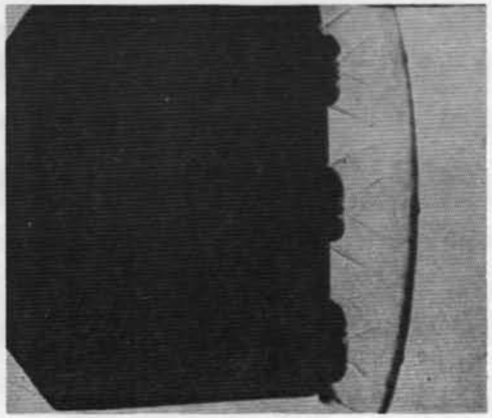
t = 0.5 μsec



t = 1.0 μsec



t = 1.5 μsec



t = 2.0 μsec

Model Velocity: 2,400 m/sec
Range Pressure: 352 torr
1.1-mm-diam Water Droplets

c. Three impacts
Figure 16. Concluded.

Table 1. High-Speed Image Intensifier/High-Speed Photopyrometer State-of-the-Art History

Time Period	Pertinent Intensifier Characteristics*	Photopyrometer Lower Measurement Limit	Remarks	References
1970	S-11 spectral response (0.35 to o.65 μm), relay lens transfer of intensified image to film	2,800 K	Initial systems	1, 5 through 7, 14, and 15
1971	S-11 spectral response, direct coupling of image to film via fiber-optics faceplate**	2,300 K	Improved light efficiency	1, 5 through 7, and 15
1974	S-20R spectral response (0.35 to 0.93 μm), fiber-optics coupled**	1,900 K	Good near-infrared response	2 and 3
1975	S-20R spectral response, fiber-optics coupled**	1,600 K	Improved version having higher gain, better near-infrared response	
1976	S-20R spectral response, channel intensifier section, fiber-optics coupled†	1,250 K	Extremely high gain	--

*The aeroballistic range/track application requires that the general intensifier type be a proximity-focused diode, gatable at exposure times down to 100 nsec or less.

**Type designation: Generation I (Gen. I)

†Type designation: Generation II (Gen. II)

Table 2. Measurement Ranges for Track G Photopyrometers

System Type	Number Available	Exposure Duration, nsec	Dynamic Range,* K	Calibration Source
Gen. I	2	1,000 100	1,600 to 3,300 1,950 to 4,000**	Graphite Arc
Gen. I	1	1,000 100	1,700 to 3,400 2,050 to 4,000**	Graphite Arc
Gen. II	1	1,000 100	1,250 to 1,900 1,500 to 2,400	Blackbody Blackbody and Graphite Arc
Gen. II	1	300 30	1,250 to 1,900 1,500 to 2,400	Blackbody Blackbody and Graphite Arc

*Dynamic range lower limit is defined at signal level twice that of background noise. Values given are for f/11 lens aperture.

**Upper limit not well established; calibration source above 3,790 K not available.